The Social Value of Offsets

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The social value of offsets

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Abstract

How much carbon should be stored in temporary and risky offsets to compensate an emission of 1 ton of CO2? We show how the Social Value of an Offset (SVO) is a well-defined fraction of the Social Cost of Carbon which depends on the offset's expected lifetime, risk of non-additionality and risk of failure. The key insight is that the SVO can be positive because delaying emissions is socially valuable. Offset projects could therefore be part of an efficient net-zero portfolio if their SVO to cost ratio exceeds the benefit-cost ratio of alternative projects. Since many offset projects are not riskless or perpetual, offset suppliers should supply transparent information about the permanence, risk and additionality of their offerings, so that the SVO can be calculated and offsets easily compared. We provide a matrix of risk correction factors to calculate the SVO for this purpose.

JEL Classification: D31, D61, H43.

Keywords: Carbon Offsets, Social Cost of Carbon, Additionality, Risk, Impermanence.

1 Introduction

To meet the target of the Paris Agreement, to limit climate change to below 1.5C of warming, governments (e.g. UK, USA, France, Germany) and financial institutions (e.g. the Glasgow Finance Alliance on Net-Zero (GFANZ)) have made commitments to a net-zero programme for carbon emissions. COP26 led to additional net-zero pledges (e.g. India). Yet meeting these targets will require concerted action in the global economy and the deployment of numerous approaches to reduce carbon emissions. Absent inexpensive technological fixes, offsets, including nature-based offsets (NBS), will be required to meet net-zero commitments.

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Unfortunately, there are considerable uncertainties associated with offsets due to the unregulated nature of the global offsets market, and the difficulties associated with establishing successful projects. NBS in forestry are seen as particularly risky options due to the absence of strong institutions on the ground to monitor, enforce and account for emissions sequestered. Offsets promise land-use change via avoided deforestation or reforestation in tropical forests, perhaps via Reduced Emissions from Deforestation and Degradation (REDD+). Empirical evidence suggests that reported emissions reductions from REDD+ projects are either vastly overstated (West et al., 2020), partial (Jayachandran et al., 2017) or minimal in relation to Nationally Defined Contributions (NDCs) (Groom et al., 2022). Over-claiming the efficacy of offsets is not confined to tropical countries either, with over-crediting occurring in Californian forest offsets (Badgley et al., 2021). The uncertainties associated with offsets lead to major difficulties in evaluating the performance and comparability of different offset schemes, and doubt about the functionality of offset markets to achieve their goal of emissions net-zero. High level initiatives, such as the Taskforce for Scaling the Voluntary Carbon Markets (TSVCM) have tried to find a common standard of integrity for offsets and ensure fungibulity in light of these difficulties, but so far to no avail.

At the core of offset fungibility is the question of how many risky or temporary offsets are equivalent to a permanent removal of emissions? An emission today which is offset by a temporary project can be thought of as a postponed emission, with the same warming effect when the project ends, but with less warming during the project. The Social Value of Offsets (SVO) stems from the value of delaying emissions and this will depend on how impermanent, risky or partially additional they are. Whether offsets are a worthwhile investment in any net-zero strategy will then depend on the comparison of the SVO with their social costs of provision. Offsets will be efficient if their Benefit-Cost Ratios outperform other carbon removal strategies. The SVO and Benefit-Cost Ratios then act as the common standard of comparison for offsets of varying quality.

Using an analytical climate-economy model (Dietz and Venmans, 2019a), we derive a simple expression for the Social Value of an Offset (SVO) that will allow this cost-benefit analysis to take place. The SVO is bounded by the value of a permanent and riskless removal of carbon from the atmosphere, measured by the Social Cost of Carbon today (SCC_0). The SVO is the SCC_0 multiplied by a correction factor reflecting macroeconomic factors (e.g. growth), future temperature paths and offset-specific characteristics: Impermanence, risk of failure and additionality. Our SVO pricing formula can be easily operationalised and we provide a matrix of correction factors for different parameter values. For example, assuming that future temperatures follow the RCP2.6 (6.0) emission scenario, the SVO of a project with a 0.5% likelihood of failing or becoming non-additional in each year and a maximum duration of 100 (50) years has 70% (33%) of the value of a riskless eternal project, and 1.4 (3) of such offsets are equivalent to a permanent carbon removal. The SVO is therefore the key to the harmonisation and fungibility of the offset market in pursuit of net-zero.

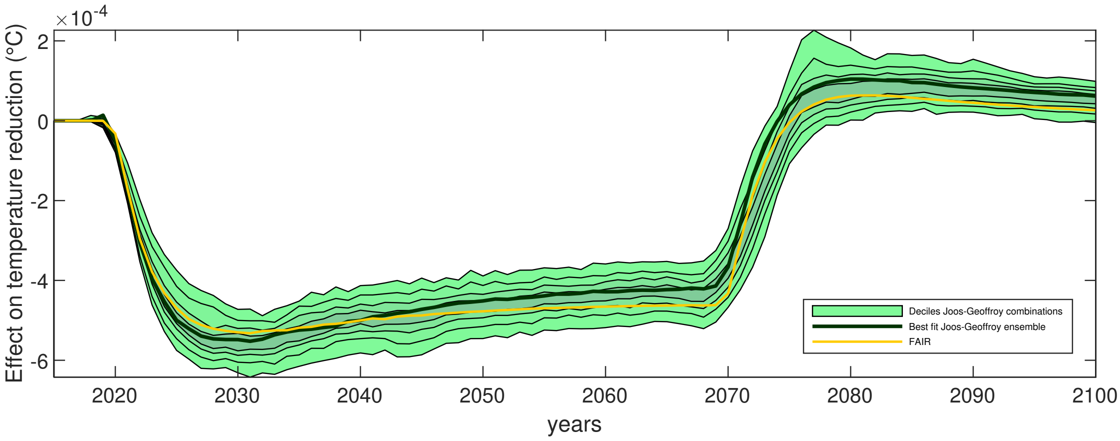

Figure 1: **The effect of an offset on warming .** The Figure shows the difference between the temperatures of the SSP1_26 background scenario and the scenario with a temporary removal project, intantaneously absorbing 1 GtCO2 in 2020 and reinjecting it in 2070. The 16 absorption models are combined with 16 energy balance models from the CMIP 5 ensemble (as in Geoffroy et al., 2013) and the figure shows the deciles of the 256 possible combinations of models. The FAIR model uses the best fit of the CMIP5 models but adds saturation of carbon sinks. The climate sensitivity of all energy balance models has been harmonized to 3.1°C. Impact response functions for other background scenarios and atmospheric CO2 concentrations are in the Appendix.

2 The effect of a temporary carbon offset on the climate

We embed our analysis of temporary emissions reductions in the latest climate models. Figure 1 shows the temperature effect of a temporary withdrawal of one unit of CO2 in 2020 which is released back into the atmosphere in 2070. The green bands show the deciles of 256 combinations of carbon absorption and thermal inertia models in the CMIP 5 modeling ensemble. It also shows the result for the FAIR model which adds the feedback that warmer and more acid seas will absorb less CO2. The graph shows that a CO2 withdrawal has a rapid cooling effect, which is more or less constant over time and stops rapidly after the CO2 is reinjected in the atmosphere after 50 years. These climate dynamics allow us to approximate the temperature response in Figure 1 by a step-function with a delay of period ξ between absorption and the temperature effect. From our own calculations, the best fit for ξ is $\xi = 3$ years for the SSP1-RCP2.6 scenario. The step-function with a delay of ξ is in line with the common assumption that warming ($T_{t+\xi}$) is proportional to cumulative CO2 emissions (S) between the pre-industrial period and time t: $T_{t+\xi} = \zeta S_t$, where ζ is the Transient Climate Response to cumulative Emissions (TCRE) (Dietz and Venmans, 2019b; Zickfeld et al., 2016).

3 The Social Value of Offsets (SVO)

The Social Cost of Carbon (SCC) is the economic valuation of the damages caused by the marginal additional ton of CO2 to the atmosphere, or alternatively the benefit of a permanent reduction of CO2 in the atmosphere. An impermanent offset will remove CO2 from the atmosphere for a limited duration.Looking into the future, an offset that is subject to the risk of failure or non-additionality will be *expected* to have a limited duration. The Social Value of an Offset (SVO) depends on the damages prevented by, or expected to be prevented by, this temporary or risky removal of CO2 from the atmosphere. The SVO is therefore closely related to the Social Cost of Carbon (SCC) and reflects the value of delaying emissions. To characterise the SVO we use an analytical Integrated Assessment Model in which the damage function, $D(T, Y)$, depends on the size of the economy (GDP), Y, and is convex and increasing in temperature, T, in line with recent research (e.g. Howard and Sterner, 2017; Burke et al., 2015). A unit of emissions at time τ will add a marginal damage ζD_T (subscripts denote partial derivatives) with a delay ξ from time $\tau + \xi$ onwards. In a warming world, the marginal damage as a result of an emission at time τ will increase over time. The SCC at time τ, SCC_τ, is defined as the sum of the discounted marginal damages from $\tau + \xi$ into the infinite future.

$$SCC_\tau = \sum_{t=\tau}^{\infty} exp\left(-r\left(t + \xi - \tau\right)\right) \zeta D_{T_{t+\xi}} \tag{1}$$

We now characterise the relationship between the SCC and the SVO for different offset projects.

An impermanent offset

If an offset were to remove 1 ton of CO2 from the atmosphere permanently at time τ, its social value would be SCC_τ. However, permanence and certainty are not characterisics of the typical offset offering (Badgley et al., 2021).Assume, therefore, that an offset removes 1 ton of CO2 at time τ_1 for υ years until this 1 ton of CO2 is re-released at time, τ_2. The SVO in this case is the present value (valued at date $t = 0$) of the damages avoided for time horizon $\tau_1 + \xi$ to $\tau_2 + \xi$:

$$SVO_{\tau_1\tau_2} = \sum_{t=\tau_1}^{\tau_2} \overbrace{e^{-r(t+\xi)}}^{Discount\ factor} \overbrace{\zeta D_{T_{t+\xi}}}^{Marginal\ damages} \tag{2}$$

The temporary project can be thought of as a permanent project at τ_1, combined with a re-release at time τ_2. The $SVO_{\tau_1\tau_2}$ is the net benefit of delay, reflecting the benefit of a permanent emissions reduction at time τ_1 minus the damages caused by the re-release of emissions at time τ_2. The $SVO_{\tau_1\tau_2}$ is therefore the difference between SCC_{τ_1} and SCC_{τ_2}in present value terms. Define x as the the average growth rate of SCC_τ between τ_1 to τ_2, the methods section shows that the SVO is simply:

$$SVO_{\tau_1\tau_2} = SCC_0 \overbrace{e^{(x-r)\tau_1}}^{Delayed\ start} \overbrace{\left(1 - e^{(x-r)(\tau_2-\tau_1)}\right)}^{Impermanence} \tag{3}$$

$SVO_{\tau_1\tau_2}$ is a corrected version of the value of a permanent reduction in emissions today, SCC_0, where the correction factor reflects: i) the delay in implementation from today until τ_1 ; and, ii) the known truncation of the project at time τ_2. This formula is valid for any trajectory of marginal damages. Two characteristics of $SVO_{\tau_1\tau_2}$ are immediately obvious from the pricing formula in Equation (3). First, $SVO_{\tau_1\tau_2}$ depends on the trajectory over time of SCC_τ. Second, because SCC_τ cannot grow faster than the discount rate (see SM), the $SVO_{\tau_1\tau_2}$ is bounded between zero and SCC_0.

An offset with failure risk

The analysis can be extended to take into account the likelihood that at any moment the offset technology could fail, e.g. reforestation or avoided deforestation is simply destroyed by force majeure, property rights failure or a change in land-use policy in situ. Suppose that in principle the offset remains temporary with a known fixed end date τ_2. Suppose also that an offset project is subject to the constant instantaneous hazard rate, ϕ, which reflects the instantaneous probability of an offset failing at time τ, conditional on having already survived until that date. By definition, the probability of the project surviving for τ years or longer is given by $P(t \geq \tau) = \exp(-\phi\tau)$. This means that at any future time τ the offset project continues to provide one ton of emissions reduction with probability $P(t \geq \tau) = \exp(-\phi\tau)$, or else has failed to offset with probability $1 - \exp(-\phi\tau)$. The duration of the offset is therefore uncertain, but ν is the maximum. The supplementary material shows that if SCC_τ increases at a constant rate x, failure risk will reduce the $SVO^{\phi}_{\tau_1\tau_2}$ as follows:

$$SVO^{\phi}_{\tau_1\tau_2} = SCC_0 \overbrace{e^{(x-r)\tau_1}}^{Delayed\ start} \overbrace{\left(1 - e^{(x-r-\phi)(\tau_2-\tau_1)}\right)}^{Impermanence} \overbrace{\frac{r-x}{r+\phi-x}}^{Failure\ risk} \tag{4}$$

An offset with non-additionality risk

The time profile of additionality risk depends on the type of project. If a project removes CO2 from a baseline in which there was no removal, such as a reforestation project, there is a risk that in the absence of the project reforestation would have occurred anyway, if forests become more productive than barren land, due to policies that existed anyway, or due to secondary forest regrowth (Poorter et al., 2021). In this case additionality risk corresponds to an earlier end of the project, very similar to the risk of failure, as shown in panel b of Figure 2. In this context, the risk of non-additionality can be framed as a hazard rate φ leading to the probability $P(t \geq \tau) = \exp(-\varphi\tau)$ that the project has

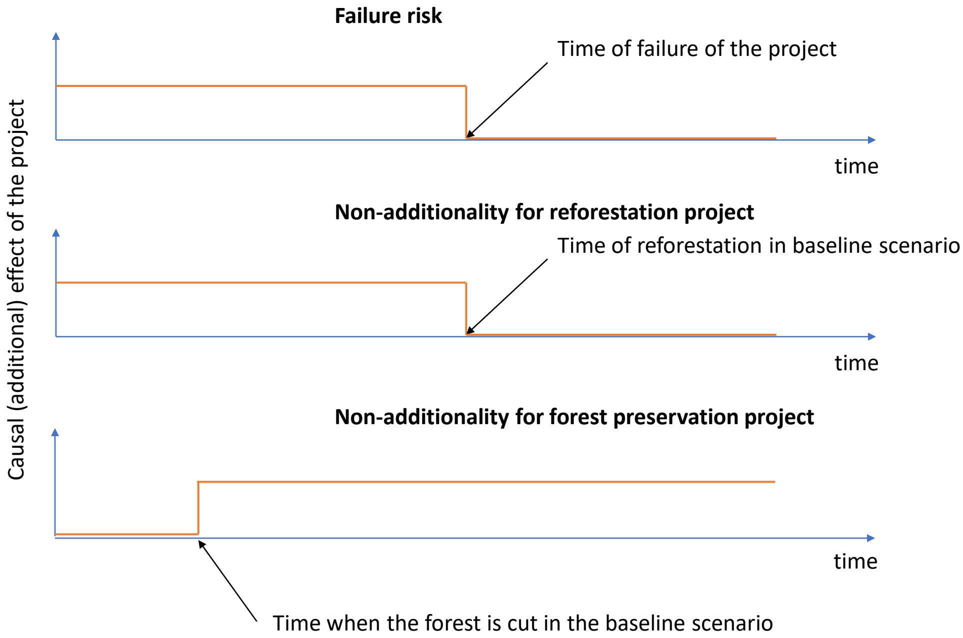

Figure 2: The time profile of additionality risk. The causal or additional effect of the project is the difference in carbon storage between the project and the baseline, i.e. what would have happened in the absence of the project.

a causal effect at least until time τ. The expression is analogous to the case of a failure risk, leading to an adjustment factor $\frac{r-x}{r-x+\phi+\varphi}$, where both failure hazard rate and the additionality hazard rate are added up (see SM). Note that our formula is also valid if ϕ and φ are both time dependent, but their sum is constant, which could happen in the intuitive case where degradation of a forestry project is more likely early on, whereas reforestation in the baseline is more likely further in the future.

Alternatively, conservation projects take as their baseline ongoing loss of forested land, and offsetting stems from avoided deforestation, under the assumption that in the baseline CO2 would have been emitted, but the project avoids these emissions. Here non-additionality occurs at the start of the project since the expected deforestation potentially would not have happened in the baseline, as depicted in panel (c) of Figure 2. Assume that without the preservation project, there is a hazard rate $\tilde{\varphi}$ that the forest would have disappeared, making the offset additional. The probability that the project has an additional (or causal) effect at time τ is therefore: $P\left(t \leq \tau\right) = 1 - \exp\left(-\tilde{\varphi}\tau\right)$. The correction factor now becomes $\left(\frac{r-x}{r-x+\phi} - \frac{r-x}{r-x+\phi+\tilde{\varphi}}\right)$ for sufficiently large τ_2.

4 A general formula for the SVO

In principle, the SVO expressions can be easily operationalised since the offset-specific parameters: τ_1, υ, ϕ, φ,and $\tilde{\varphi}$, for any given offset technology, and the macro-economic and climate parameters, r, SCC_0, x, can all be estimated. However, while providing a straightforward means of explaining the principles underpinning the SVO, the asumption that the SCC grows at a constant rate x does not necessarily reflect typical climate scenarios, such as the RCPs. In this section we generalise the formula to allow for any any temperature path and different trajectories for the SCC. The general formula also provides more detailed project specific characteristics than the step-function used so far, to account for gradual absorption and re-release.

With climate damages proportional to GDP, Y, and quadratic in temperature: $D = Y\left(1 - \exp\left(-\frac{\gamma}{2}T\right)\right)$ (Howard and Sterner, 2017), the marginal damage for a unit of CO2 emission at time t is linear: $\zeta D_T = \zeta\gamma YT$. Suppose also that absorption and release of CO2 is reflected by a time profile q_t, indicating the stock of carbon absorbed by the successful project. In this case the general formula for the SVO correction factor accounting for impermanence, failure and non-additionality risks becomes:

$$\frac{SVO^{\phi,\varphi}_{\tau_1\tau_2}}{SCC_0} = \frac{\sum_{t=\tau_1}^{\tau_2} \overbrace{e^{-r(t+\xi)}}^{Discount\ factor} \overbrace{e^{-(\phi+\varphi)(t-\tau_1)}}^{\substack{Failure\ and\ additionality\\ risk\ at\ end}} \overbrace{\left(1 - e^{-\tilde{\varphi}(t-\tau_1)}\right)}^{Additionality\ risk\ at\ start} \overbrace{q_t}^{Quantity\ stored} \overbrace{\zeta\gamma Y_{t+\xi} T_{t+\xi}}^{damages}}{\sum_{t=0}^{\infty} e^{-r(t+\xi)} \zeta\gamma Y_{t+\xi} T_{t+\xi}} \quad (5)$$

Interestingly, the two most difficult parameters to parameterise, the TCRE, ζ, and the damage coefficient, γ, do not affect the offset correction factor for impermanence and risk. Only the future temperature and GDP paths are needed to operationalise this specific formula. Furthermore, the formula easily accommodates further project specific factors, such as time dependence of the failure and non-additionality risks, while ζ can be replaced by the exact time profile of the temperature impact response function in Figure 1.

To illustrate the flexibility of Equation (5) the Supplementary Materials provide a simple excel spreadsheet that calculates the adjustment factor for different temperature paths: the IPCC's RCP2.6, RCP4.5 and RCP6 scenarios, and for different parameter values for project specific characteristics. Table 1 summarises the adjustment factors for a subset of parameters values and temperature paths. The Supplementary Materials (SM: Section 2) provides closed-form solutions for the SVO assuming linear and exponential temperature paths. For any given emissions scenario, the conversion factor diminishes as the offset has shorter duration and a higher risk of failure or non-additionality. An offset of duration of 25 years with a 0.5% annual risk of failure or non-additionality has a correction factor of

23% in RCP 2.6 (1.8C), which drops to 16% in RCP 6 (3.1C), which has higher marginal damages in the future when the project releases its carbon back in the atmosphere. Note that in high emission scenarios although the conversion factor is lower, the absolute dollar value of an offset will be higher. Table 1 allows a carful comparison of absolute and relative values.

The concept of the SVO and the general formula provide an answer to the question of how much carbon should be held in offsets compared to alternative mitigation strategies. A correction factor of z means that in order to offset the equivalent of 1 ton of carbon $1/z$ offsets would have to be purchased. Table 1 shows that this can mean anything from a near one-to-one relationship between offsets projects and permanent carbon removal, to a situation where 10 offsets, each claiming to offset 1 ton of carbon, would have to be purchased to be equivalent to a permanent emissions reduction. It is important to recognise that this equivalence is in the aggregate. Given uncertainty, some individuals will end up reducing emission by more than 1 ton in the end, others by less, but on average the overall impact would be a 1 ton emissions reduction per person. Table 1 makes the rate of conversion explicit. For a full picture of the efficiency of offsets compared to alternatives, a benefit-cost analysis is required, and interventions can be ordered in terms of there benefit-cost ratios.

5 Uncertainty

In this section we consider how the SVO is affected when there is uncertainty in future emissions paths/temperature, economic growth and the project level storage of carbon, and when each is correlated with other aspects of the project, like the failure rate. Table 2 shows (see Supporting Material (S5) for technical details) that when there is uncertainty over the future temperature path, $\sigma_T > 0$, but this is independent of consumption growth, $\rho_{c,T} = 0$, and the success of the project, $\rho_{q,T} = 0$ (q_t in Equation 5), the expected (mean) temperature path of those shown in Equation (5) is appropriate to calculate the SVO. The SVO is therefore unaffected. This is also the case as when there is uncertainty over the quantity of carbon stored by the project. $\sigma_q > 0$. By contrast, when future consumption is uncertain $\sigma_c > 0$, but uncorrelated to future temperatures and failure rates, it is appropriate to decrease the discount rate to reflect the demand for precautionary savings (Arrow et al., 2013). This increases the SVO. However, since the SCC includes damages that are further in the future, this will affect the SCC more than the SVO, and the correction factor in Equation (5) will slightly decrease. If, however, there is a positive correlation between future temperature and consumption, $\rho_{c,T} > 0$, because higher production leads to higher business as usual emissions, the precautionary effect of uncertainty may be reduced or even reversed. In such cases a positive systematic risk premium could enter the social discount rate because the benefits of emissions reductions are more likely to occur in richer future states of the world, where they are valued less in terms of marginal utility (van den Bremer and van der Ploeg, 2021). Also at the project level, if the likelihood of failure or non-additionality is larger in a warming world, $\rho_{q,T} < 0$, the SVO and the correction factor decreases. This could be the case if institutional capacity in the future affects both the ambition of future climate policy and enforcement of projects. The size of this effect is shown in Table 1. Care is needed, therefore, in evaluating the effect of uncertainty on the SVO.

Finally, if individual investors apply a private, higher risk premium to risky projects and value projects below their social value, the global outcome will be inefficient. This is because in the social optimum diversifiable risk is irrelevant: the early failure of one project will be offset by the later failure of another project, and only aggregate emissions have an impact on welfare. From this perspective, for a given willingness to pay to reduce climate impacts, it is best to select the project with the largest expected welfare effect from delayed damages.

6 Cost effectiveness analysis does not value the timing of damages

Climate change mitigation is frequently viewed in terms of Cost-Effectiveness Analysis (CEA), which minimizes abatement costs to keep warming below a target level. For instance, the carbon price in the UK reflects the marginal abatement cost of meeting a net zero target by 2050. CEA is often seen as a useful climate policy tool because it is easier to agree on a temperature target than to agree on the size of damages and the discount rate (Aldy et al., 2021). However, in the case of offsets a temporary project which ends before warming constraint binds does not help achieve the overall target, since it simply delays emissions. From this valuation perspective offsets will appear to have no value whatsoever. Technically, this valuation problem appears in our formula for the SVO as the case when the accounting price of carbon increases at the discount rate, a feature of a cost-minimising abatement strategy. It is easily seen that Equation (3) is equal to zero in this case. This seemingly counter-intuitive result should not be interpreted as an indication that offsets have no value, but rather as a failure to value carbon emissions properly. CEA minimises costs and does not maximize welfare, it therefore disregards the welfare value of delaying damages. In the supplementary material we show that on a welfare maximizing trajectory the SCC always increases at a rate that is lower than the discount rate: $r > x$. The Supplementary Information further shows that a CEA can also overvalue projects if they extend beyond the point at which the target is met, since from this point onwards the carbon price remains constant ($r > x = 0$). This too gives misleading results for the valuation of offsets.

IPCC Scenario	Risk at start	Risk at end	SVO Correction factors (max.duration, v)				SCC ($\$/tCO_2$) Damages ($\gamma$)	
(Temp in 2100)	$\tilde{\varphi}$	$\phi+\varphi$	25	50	100	∞	γ=0.0077	γ=0.0025
RCP 2.6	1000(low risk)	0	24%	44%	70%	100%	109	35
(1.8°C)		0.0025	23%	42%	63%	83%	109	35
		0.005	23%	40%	58%	71%	109	35
	0.5	0	23%	43%	69%	99%	109	35
		0.0025	22%	40%	62%	82%	109	35
		0.005	21%	38%	56%	69%	109	35
	0.25(high risk)	0	21%	41%	67%	97%	109	35
		0.0025	20%	39%	60%	80%	109	35
		0.005	20%	36%	54%	68%	109	35
RCP 6.0	1000	0	17%	34%	64%	100%	161	52
(3.1°C)		0.0025	17%	32%	57%	81%	161	52
		0.005	16%	31%	51%	67%	161	52
	0.5	0	16%	33%	63%	99%	161	52
		0.0025	16%	31%	56%	80%	161	52
		0.005	15%	30%	50%	66%	161	52
	0.25	0	15%	32%	61%	98%	161	52
		0.0025	14%	30%	55%	78%	161	52
		0.005	14%	28%	49%	65%	161	52
Uncertain RCP	1000	0	20%	38%	66%	100%	138	45
		0.0025	19%	35%	58%	79%	138	45
		0.005	18%	33%	51%	64%	138	45
	0.5	0	19%	38%	66%	100%	138	45
		0.0025	19%	35%	58%	78%	138	45
		0.005	18%	33%	51%	64%	138	45
	0.25	0	18%	37%	65%	99%	138	45
		0.0025	18%	34%	57%	77%	138	45
		0.005	17%	32%	50%	63%	138	45

Table 1: Adjustment factors for non-permanence and risk. We assume a quadratic damages proportional to GDP $exp\left(-\frac{\gamma}{2}T^2\right)$ with damage parameters of Howard and Sterner (2017) (Column 8) as well as Nordhaus (2017) (Column 9). Temperature pathways evolve according to SSP1-RCP2.6; SSP4-RCP3.4; SSP4-RCP6.0 and an uncertain temperature path (Riahi et al. 2017, www.https://tntcat.iiasa.ac.at). Other parameters are $r = 3.2\%; \tau_1 = 3year; \zeta = 0.0006°C/GtCO_2; GDPgrowth = 2\%; T_0 = 1.2°C$. We use Equation (5) . For $\tilde{\varphi} =$ [0.5 0.25] the likelihood that the project is additional after 5 years is 92% and 71% respectively. For $\varphi + \phi =$ [0.0025 0.005] the likelihood that the project is additional after 50 years is 78% and 88% respectively. Under uncertainty, we assume a temperature path following one of the 3 RCP's with equal probability and a hazard rate with the same mean but increasing in temperature $\varphi_{uncertain} = \varphi_{certain}\left(0.5 + 0.5T/\bar{T}\right)$, where $\bar{T} = 2.01°C$,i.e. mean warming of the next 80 years in the 3 RCP's.

	Uncertain temperature*	Uncertain carbon stock	Uncertain consumption**	Consumption and temp positively correlated**	Offset failure more likely in a hotter world
	$\sigma_T > 0; \rho_{q,c} = \rho_{T,c} = 0$	$\sigma_q > 0; \rho_{q,c} = \rho_{q,T} = 0$	$\sigma_c > 0; \rho_{c,T} = \rho_{c,q} = 0$	$\rho_{c,T} > 0$	$\rho_{q,T} < 0$
SVO	0	0	↗	↘	↘
SVO/SCC	0	0	↘	↗	↘

*SVO increases and SVO/SCC decreases if total damage function is a power function with a power beyond 2.
** Effects are zero for $\eta = 1$ and reversed for $\eta < 1$

Table 2: **Overview of uncertainty effects:** Quadratic total damage function and $\eta > 1$ assum. We consider mean-preserving spreads for an increase in uncertainty and

7 Conclusion

A simple expression has been developed that provides the social value of an offset capturing its duration, likelihood of failure and its potential for non-additionality. While these factors do conspire to reduce the value of a ton of carbon sequestered via an offset, they do not necessarily make offsets valueless. In fact, the paper directs analysis towards the empirical questions associated with the time horizon, and the likelihoods of curtailed values from failure and non-additionality. Offsets have a role to play as long as they provide value for money and a sufficient benefit from their delaying of emissions. From the perspective of public sector appraisal offsets may well have an important role to place where their Benefit-Cost Ratio is higher than other alternatives. Despite the fact that SVO is less than the SCC, offsets may still be competitive with other technologies where their costs of provision are low. Careful valuation of the SVO is required to make this decision, and offset providers should provide information on the risks and expected time-horizons for each of their offerings, nature-based or otherwise. With such information, our formula could provide a mechanism to harmonise, make fungible and regulate offsets, and help gauge the extent to which they should contribute to the targets of the Paris Agreement and related net-zero commitments. Of course the social value nature-based carbon offsets may well be much higher because of the co-benefits of biodiversity and ecosystem service provision. These need to be weighed against the advantages on the other side of learning by doing in the pursuit of new technological solutions, not forgetting that learning by doing also occurs in the implementation of nature-based solutions.

Materials and Methods

Proof of Equation (3)

Adding and subtracting the same sum over $[\tau_2, \infty]$ in Equation (2) and multiplying by $exp\left(-r\tau\right)$outside the sum and by $exp\left(r\tau\right)$ inside the sum, we obtain:

$$SVO_{\tau_1\tau_2} = exp\left(-r\tau_1\right) * \sum_{t=\tau_1}^{\infty} exp\left(-r\left(t+\xi-\tau_1\right)\right)\zeta D_{T_{t+\xi}} - exp\left(-r\tau_2\right)\sum_{t=\tau_2}^{\infty} exp\left(-r\left(t+\xi-\tau_2\right)\right)\zeta D_{T_{t+\xi}} \quad (6)$$

Given the definition of SCC_τ in (1), $SVO_{\tau_1\tau_2}$ simplifies to:

$$SVO_{\tau_1\tau_2} = exp\left(-r\tau_1\right)SCC_{\tau_1} - exp\left(-r\tau_2\right)SCC_{\tau_2} \quad (7)$$

$SVO_{\tau_1\tau_2}$ is simply the difference between the present values of SCC_{τ_1} and SCC_{τ_2}. Define x as the mean growth rate of the SCC between time τ_1 and τ_2 x: $SCC_{\tau_2} = SCC_{\tau_1}exp(x(\tau_2 - \tau_1))$, Substituting out SCC_{τ_2}in Equation (7) results in Equation (3).

Proof that if marginal damages increase at a constant rate x, the SCC increases at the same rate.

For notational convenience we will switch to continuous time.If the marginal damages increase exponentially at rate x, the SCC at time τ is:

$$SCC_\tau = \int_{t=\tau}^{\infty} \exp\left(-r\left(t+\xi-\tau\right)\right)\zeta D_{T_{\tau+\xi}} \exp\left(x\left(t-\tau\right)\right)dt$$

where $D_{T_\tau}$is the marginal damage at time τ. The SCC at time τ can then be re-written as:

$$SCC_\tau = \frac{\exp\left(-r\xi\right)}{r-x}\zeta D_{T_{\tau+\xi}} \quad (8)$$

from which it follows that:

$$SCC_\tau = \frac{\exp\left(-r\xi\right)}{r-x}\zeta D_{T_{0+\xi}} e^{x\tau} = SCC_0 e^{x\tau} \quad (9)$$

In the case of the seminal model by Golosov et al. (2014) model or Traeger (2021), x corresponds to the growth rate of GDP. When climate damages are quadratic and are proportional to GDP, x corresponds to the growth rate of GDP plus the growth rate of temperature.

Derivation of SVO with failure risk

By multiplying each time period with the probability that the project has not failed $e^{-\phi(t-\tau_1)}$ Equation (2) becomes:

$$SVO^{\phi}_{\tau_1\tau_2} = \exp\left(-r\tau_1\right) \int\limits_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi\right)\left(t-\tau_1\right) - r\xi\right) \zeta D_{T_{t+\xi}} dt$$

In the case of exponentially increasing marginal damages $D_{T_{t+\xi}} = D_{T_{\tau+\xi}} e^{x(t-\tau)}$ we obtain an exponential function in the integral, which we can solve

$$SVO^{\phi}_{\tau_1\tau_2} = \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} \int\limits_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi-x\right)\left(t-\tau_1\right)\right) dt \tag{10}$$

$$= \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} \left[\frac{1-\exp\left(-\left(r+\phi-x\right)\left(\tau_2-\tau_1\right)\right)}{r+\phi-x}\right]. \tag{11}$$

We can now write the result as a function of the SCC using Equation (8)

$$SVO^{\phi}_{\tau_1\tau_2} = SCC_{\tau} \exp\left(-r\tau_1\right) \left[1-\exp\left(-\left(r+\phi-x\right)\left(\tau_2-\tau_1\right)\right)\right] \frac{r-x}{r+\phi-x}. \tag{12}$$

From here the formula in the text follows assuming that the SCC grows at a rate x. It is straightforward to see that this results also holds for constant marginal damages, i.e. for $x = 0$. The SM derives formulas for other paths of marginal damages.

Derivation of SVO with additionality risk

Additionality risk is taken into acount by multiplying each period by the probability $\left(1-e^{\tilde{\varphi}(t-\tau_1)}\right) e^{-\phi(t-\tau_1)}$ where ϕ is the hazard rate for both project failure and non-additionality at the end and $\tilde{\varphi}$ governs the risk of non-aditionality at the start. Equation **??** now becomes

$$SVO^{\phi}_{\tau_1\tau_2} = \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} * \tag{13}$$
$$\int\limits_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi-x\right)\left(t-\tau_1\right)\right) - \exp\left(-\left(r+\phi+\tilde{\varphi}-x\right)\left(t-\tau_1\right)\right) dt$$

$$= \exp\left(-r(\tau_1 + \xi)\right) \zeta D_{T_{\tau_1+\xi}} \quad * \tag{14}$$
$$\left[\frac{1 - \exp\left(-\left(r + \phi - x\right)\left(\tau_2 - \tau_1\right)\right)}{r + \phi - x} - \frac{1 - \exp\left(-\left(r + \phi + \tilde{\varphi} - x\right)\left(\tau_2 - \tau_1\right)\right)}{r + \phi + \tilde{\varphi} - x}\right]$$

We can now write the result as a function of the SCC using Equations 8 and 9

$$SVO^{\phi}_{\tau_1\tau_2} = SCC_0 \overbrace{\exp\left(-(r - x)\tau_1\right)}^{\textit{Delayed start}} \overbrace{\left(1 - \exp\left(-\left(r + \phi - x\right)\left(\tau_2 - \tau_1\right)\right)\right)}^{\textit{Impermanence}} \quad * \tag{15}$$
$$\left[\overbrace{\frac{r - x}{r + \phi - x}}^{\substack{\textit{Failure risk or} \\ \textit{Additionality at end}}} - \overbrace{\frac{r - x}{r + \phi + \tilde{\varphi} - x} \frac{1 - \exp\left(-\left(r + \phi + \tilde{\varphi} - x\right)\left(\tau_2 - \tau_1\right)\right)}{1 - \exp\left(-\left(r + \phi - x\right)\left(\tau_2 - \tau_1\right)\right)}}^{\textit{Additionality risk at start}}\right]$$

Note that ϕ slightly increases our 'early end' factor, because the project may fail before time τ_2 in which case the impermanence becomes irrelevant. Similarly, the second factor in the 'additionality risk at start' term reduces the effect of impermanence (τ_2), taking into account that if the project does not start before τ_2, the impermanence is irrelevant. Therefore, for combinations of τ_2 and $\tilde{\varphi}$ which make it unlikely that the project never starts, the correction factor for additionality risk will converge to $\frac{r-x}{r+\phi-x} - \frac{r-x}{r+\phi+\varphi-x}$.

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Supporting Material

S1. Climate dynamics of a temporary withdrawal of CO2

Consider the simple case of a temporary offset that removes a single ton of CO2 at time $t_1 = 0$, only to release it again at time t_2, where $t_2 - t_1 = \upsilon$. Figure 3 uses 16 climate models from the CIMP 5 ensemble (Joos et al., 2013; Geoffroy et al., 2013) to illustrate the complex impact on the climate system on emissions and temperatures of a 1GtCO2 reduction in 2020 for a period of υ =50 years: after 50 years the offset ends and the emissions are re-released, compared to a no-offset world. Figure 3 shows the temperature effect over time of a temporary withdrawal of 1 GtCO2 in 2020

Firstly, Figure 3a reflects the baseline against which the offset's impact is evaluated: the pre-offset emissions and temperature (warming) path. Figure 3b shows the impact of the offset on CO2 concentration: i.e. the difference between offset and baseline scenarios. The shape of the response curves can be understood as follows. Atmospheric CO2 absorption by oceans and plants happens faster under higher CO2 concentration, so any difference in CO2 concentration between scenarios will fade out over time. The opposite is true for a negative pulse. In Figure 3b the immediate effect of 1GtCO2 removed in 2020 reduces over time, and the net effect is reduced over time. After 50 years, the effect is 60% of the initially absorbed quantity of CO2. Next, 1 GtCO2 is re-released into the atmosphere as the offset ends, and atmospheric CO2 concentration is at first higher than the original concentration, but again this difference fades over time. Figure 3c show the impact on temperature, where the dynamics reflect recent findings that show that temperature responses to emissions pulses are relatively rapid and persistent (Ricke and Caldeira, 2014). The cooling effect occurs with a delay of 5 years due to the thermal inertia, after which the effect on temperature is more or less constant, reflecting the balancing of the countervailing effects of thermal inertia and absorption dynamics. After 50 years, when the GtCO2 is re-released, these dynamics are reversed. The overshoot of CO2 concentration leads to a rapid energy forcing and curtails the offset's cooling effect within 5 years without a large temperature overshoot. The overall effect of the offset on temperature resembles a step function. [1]

[1] Zickfeld et al. (2021) describe differences between positive and negative emissions, which are very small for small emission pulses.

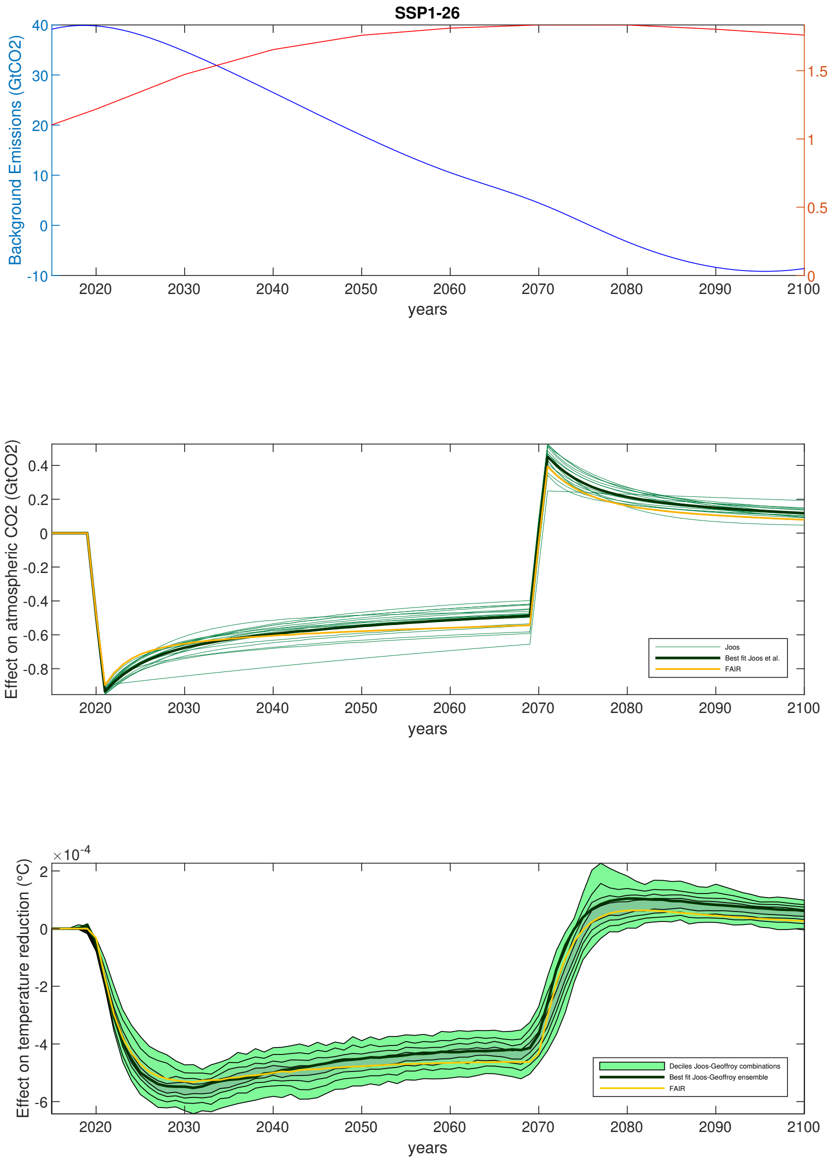

Figure 3: **The effect of an offset on atmospheric CO2 concentrations and on warming for the SSP1_26 background scenario.** Figure a shows the background emissions and temperature, following the SSP1-26 scenario. Figure b shows the difference between CO2 concentration of the background scenario and the scenario with a temporary removal project, instantaneously absorbing 1 GtCO2 in 2020 and reinjecting it in 2070. The 16 green lines correspond to 16 carbon absorption models in the CMIP 5 modeling ensemble described by Joos et al. (2013). The yellow line is the FAIR model, which is based on the the best fit of the CMIP 5 ensemble, but adds a carbon sink saturation feedback. Figure c shows the difference between the temperatures of the background scenario and the scenario with the removal project. The 16 absorption models are combined with 16 energy balance models from the CMIP 5 ensemble (as in Geoffroy et al., 2013) and the figure shows the deciles of the 256 possible combinations of models. The FAIR model uses the best fit of the CMIP5 energy balance models. The climate sensitivity of all energy balance models has been harmonized to 3.1°C. Impact response functions for other background scenarios are in the Appendix.

S2. Climate dynamics under other background emissions

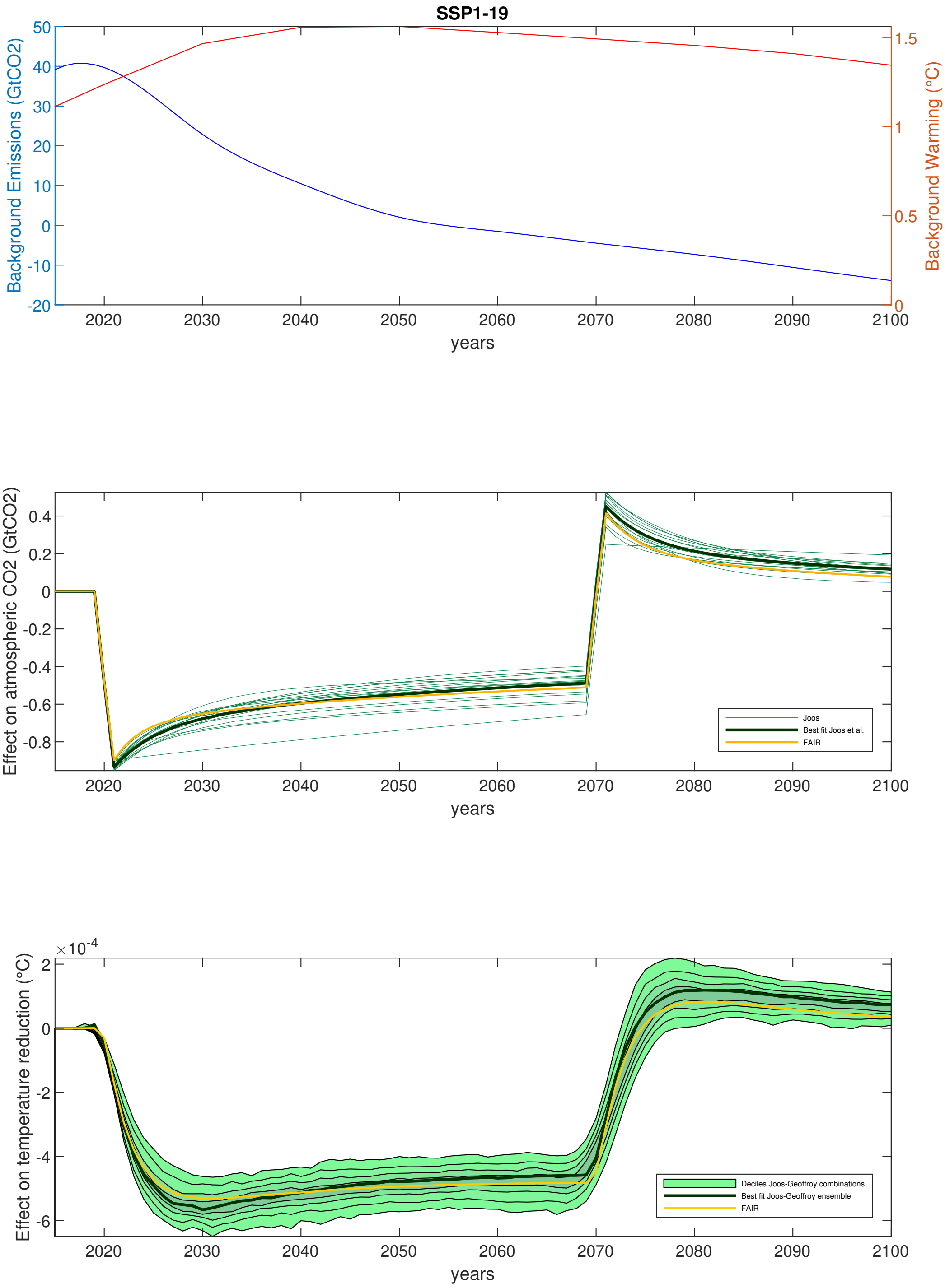

Figure 4: SSP 1-19

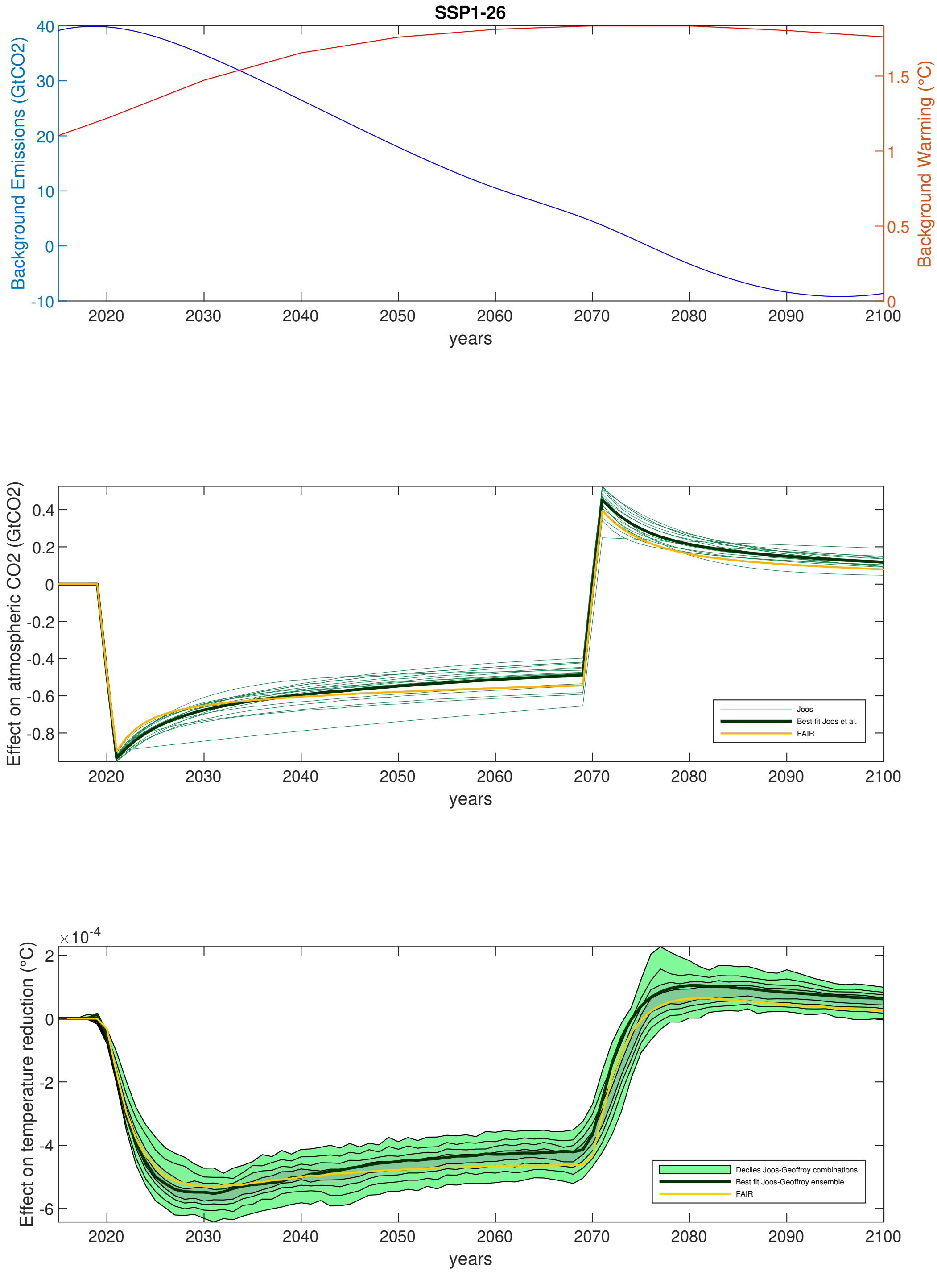

Figure 5: SSP 1-26

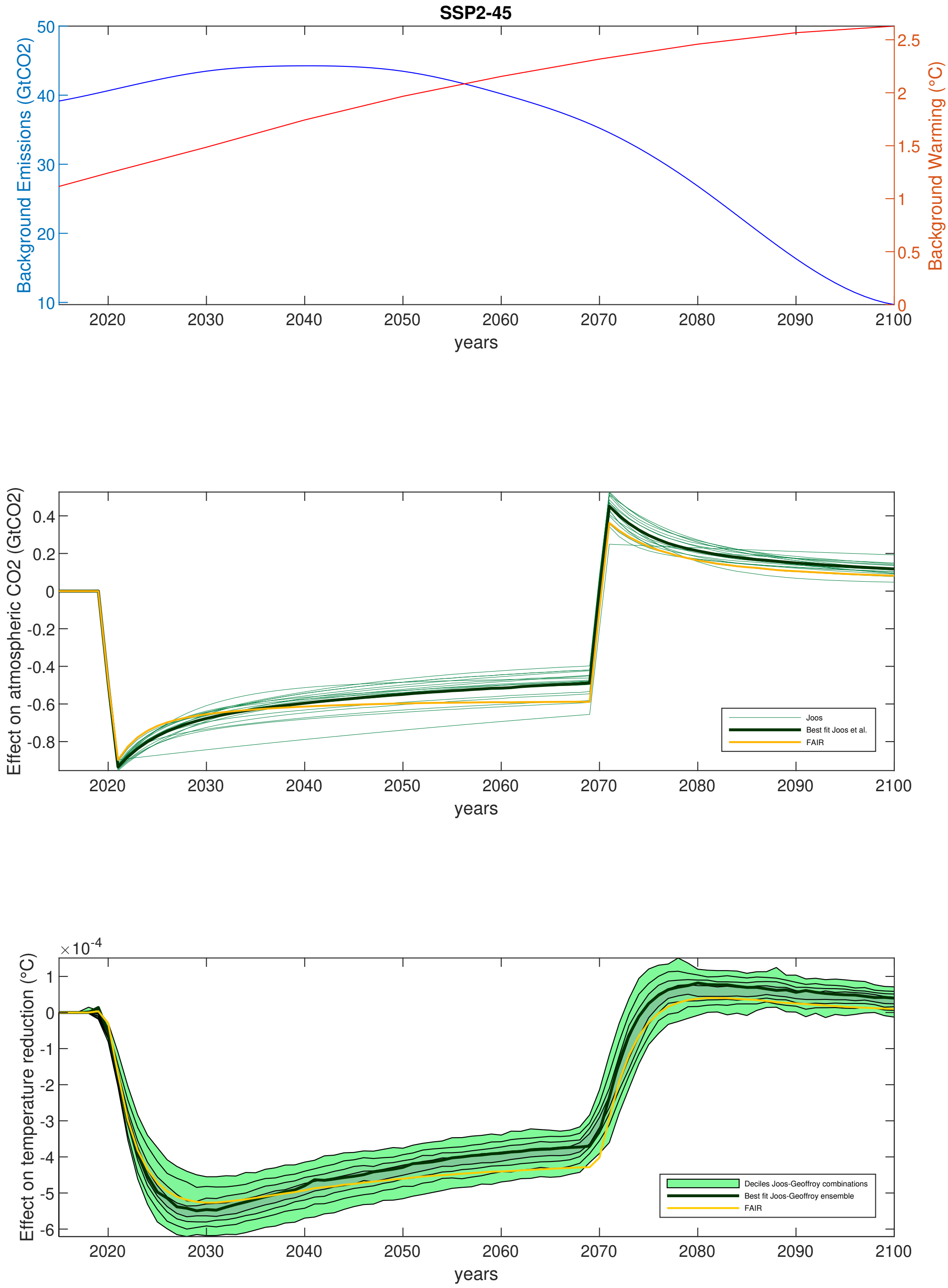

Figure 6: SSP 1-45

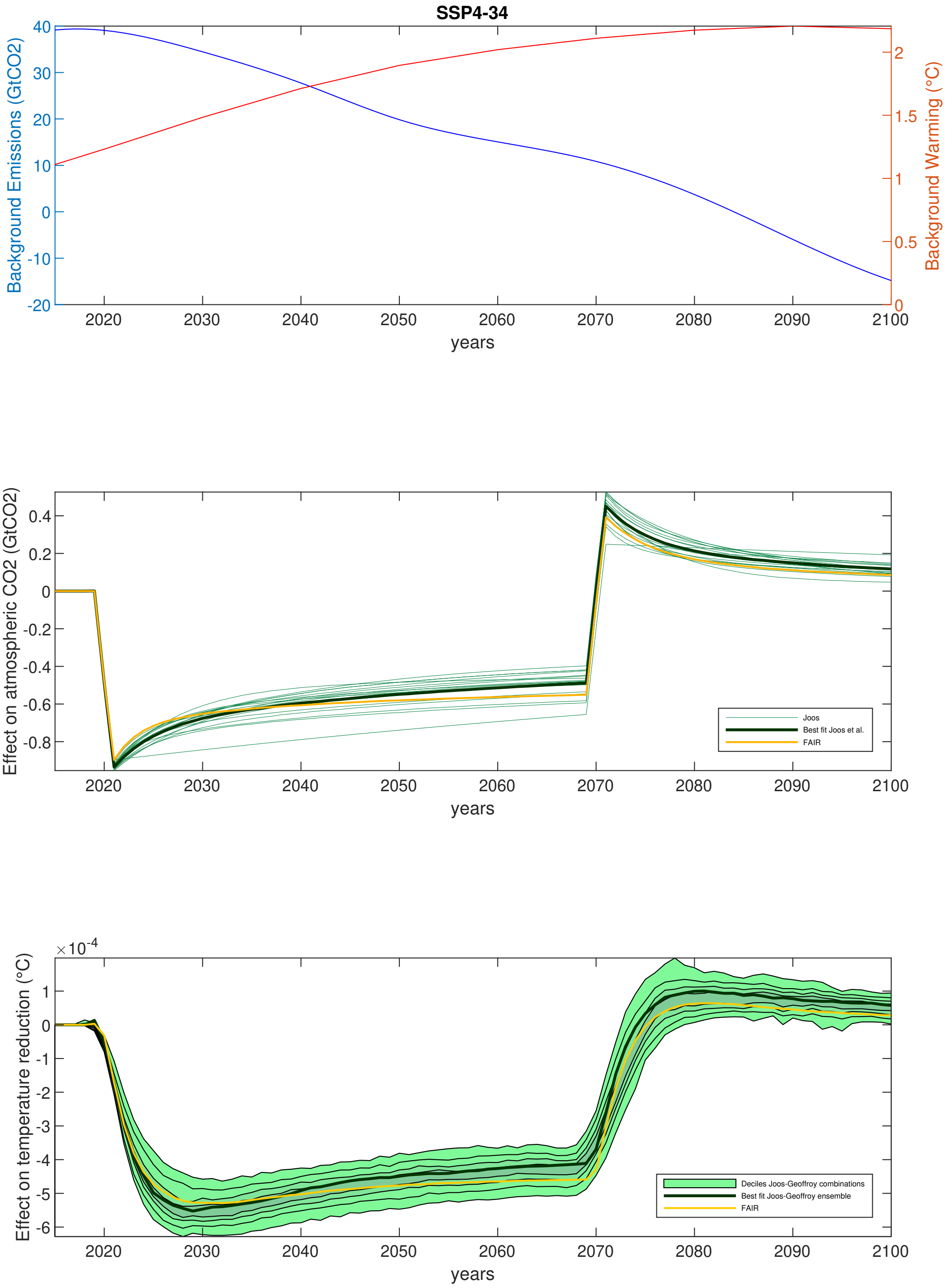

Figure 7: SSP4-34

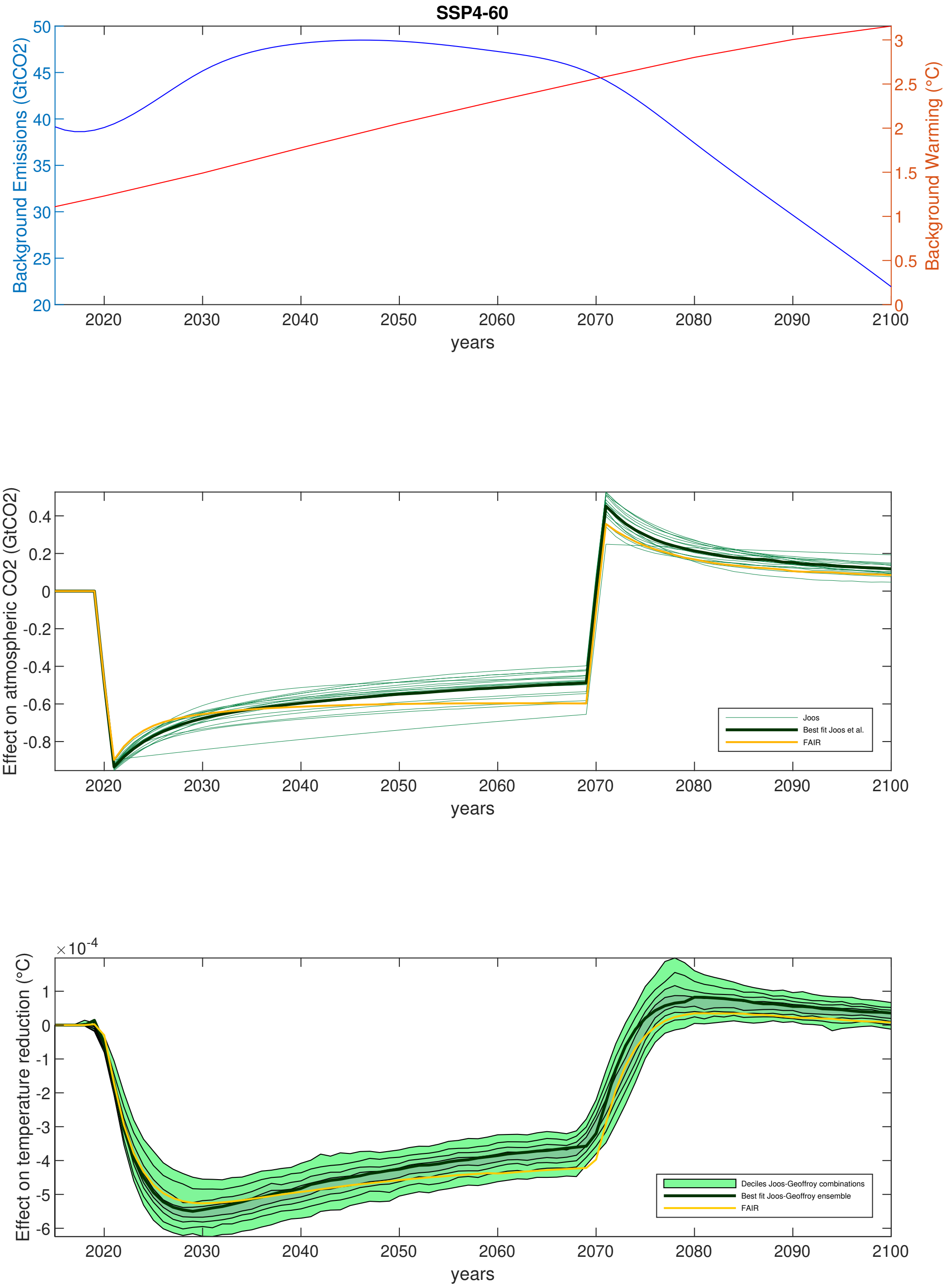

Figure 8: SSP 4-60

S3. Formula and growth rate of the SCC on optimal and non-optimal trajectories

The dynamics of the social cost of carbon are explained in the context of a simple control problem of a stock pollutant. We assume that warming T is proportional to cumulative emissions S, $T = \zeta S$, with ζ the Transient Climate Response to Cumulative Emissions. This means that we abstract from the short delay between emissions and warming ($\xi = 0$). From the definition of cumulative emissions we have $\dot{S} = E$. The damages associated with the pollutant (e.g. CO2 equivalents) are given by the function $D(T)$, where T is and $\frac{\partial D(T)}{\partial T} = D_T \geq 0$ and $\frac{\partial^2 D(T)}{\partial T^2} = D_T \geq 0D > 0$. Since temperature is linear function of cumulative emissions, applying the chain rule gives $D_S = \zeta D_T$ The economic benefits of emitting the pollutant are given by $B(E)$where E are emissions at any given point of time, and $\frac{\partial B(E)}{\partial E} = B_E(E) \geq 0$ and $\frac{\partial^2 B(E)}{(\partial E)^2} = B_{EE}(E) \leq 0$. The net benefits of economic activity that requires the emission of CO2e is therefore: $B(E) - D(S)$. Given this simple set-up, the control problem is to maximize the present value of the net benefits from emitting the stock pollutant taking into account the constraints on the stock dynamics, the technology associated with extraction of fossil fuels, the net benefits function, and the discount rate r. The net benefits are measured in cash equivalents and so the appropriate discount rate is the consumption rate of discount, and for the purposes of the exposition, the discount rate is assumed to be invariant to the time horizon being evaluated. the control problem therefore takes the following form:

$$V = \max_{E} \int_{t=\tau}^{\infty} \exp\left(-r\left(t-\tau\right)\right)\left(B\left(E\left(t\right)\right) - D\left(S\left(t\right)\right)\right) dt \tag{16}$$

$$s.t.$$

$$\dot{S} = E$$

$$S(0) = S_0$$

The optimum path of extraction and stock accumulations can be solved using optimal control methods. We have assumed the that limit on fossil fuel is not binding, that it is optimal not to burn all reserves.The solution stems from the Maximum Principle associated with the current value Hamiltonian:

$$H(E, S, \mu) = \left(B\left(E\left(t\right)\right) - D\left(S\left(t\right)\right)\right) + \mu\left(E\right) \tag{17}$$

where μ is the shadow value of the stock: the change in the value of the maximand in Equation (16) as a result of a marginal change in the stock, S. The interior solution for this problem is given by:

$$\frac{\partial H}{\partial E} = B_E + \mu = 0 \tag{18}$$

$$-\frac{\partial H}{\partial S} = \dot{\mu} - r\mu = D_S \tag{19}$$

$$\lim_{t\to\infty} \mu\left(t\right)\exp\left(-rt\right)S\left(t\right) = 0 \tag{20}$$

From 18 we know that the shadow price of the stock is negative because $B_E > 0$. This makes sense because the stock in this case is a pollutant, and so additional units of the stock are detrimental to net benefits, other things equal. Combining 18 and 19 leads to the following expression for the dynamics of the shadow price μ:

$$\frac{\dot{\mu}}{\mu} = \frac{D_S\left(S\right)}{\mu} + r \tag{21}$$

which shows that the shadow price of the stock pollutant increases at a rate which is lower than the rate of discount, r, because $\mu < 0$. It remains to be shown that μ has the interpretation of the Social Cost of Carbon as presented in the main text in Equation (1). Defining $\theta = -\mu$ and solving out the differential Equation on (21) shows that (See Hoel 2016, p8-11):

$$\theta\left(\tau\right) = \int_{t=\tau}^{\infty} exp\left(-r\left(t-\tau\right)\right)D_S\left(S(t)\right)dt \tag{22}$$

which is identical to Equation (22). In an optimal control problem, the shadow price on the stock of cumulative emissions is the Social Cost of Carbon, which is also the benefit of reducing this stock by a marginal ton.

Note that Equation (22) has a straightforward interpretation: the social cost of carbon is the discounted sum of all marginal damages and it is easy to see that this also applies to marginal projects on non-optimal temperature paths. Hence, Equation (21), which is just the time derivative of Equation (22), shows that the SCC on non-optimal temperature paths also increases at a lower rate than the discount rate (as long as marginal damages are positive).

S4. The SVO with different assumed temperature, emission and marginal damage paths

Marginal damages grow at a constant rate, x

The exposition of SVO in Section 3 has assumed for simplicity a marginal damage growing at a constant rate x. In this appendix, we look at conditions which are compatible with

Table 3: Mean growth rates of the SCC for different temperature paths and time frames. We assume a quadratic damage function, proportional to GDP, which increase at 2%. For a stable temperature, the SCC will increase at the growth rate of GDP. The discount rate is 3.2%. Since RCP scenarios are only defined until 2100 we assume a linear trend between 2095 and 2120 and constant temperatures thereafter.

	RCP2.6	RCP4	RCP6	RCP8.5
2020-2040	2.2%	2.4%	2.5%	2.8%
2020-2060	2.1%	2.3%	2.4%	2.7%
2020-2080	2.0%	2.3%	2.4%	2.6%
2020-2100	2.0%	2.2%	2.3%	2.5%

this assumption.

Consider the quadratic damage function in section 4 $D_T = \gamma YT$. Assume income grows at a constant rate g and temperature grows at constant rate y. As a result, marginal damages are $D_T = \gamma Y_0 S_0 e^{(g+y)t}$ and will grow at a constant rate $x = g + y$.

What if the damage function would not be quadratic? Assume that the damage function is a general power function of power θ, $D = \gamma YT^{\theta}$, that temperature raises at rate y and the economy at rate g. Then $D_T = -\gamma\theta YT^{(\theta-1)} = \theta\gamma\zeta Y_0 S_0 e^{(g+(\theta-1)y)t}$ and the growth rate of marginal damages is again constant and equal to $x = g + (\theta - 1)y$. With these assumptions, the SVO pricing formulas in Section 3 are appropriate.

Which emission paths will lead to a temperature path with a constant growth rate? Since emissions are the time derivative of cumulative emissions and using the approximation $T = \zeta S$, we can write $S_t = S_0 e^{yt} \Leftrightarrow E_t = \dot{S}_t = \underbrace{yS_0}_{E_0} e^{yt}$. Therefore, a temperature increasing at rate y requires emissions to increase at the same rate, with initial ($t = 0$) emissions $E_0 = yS_0$. With emissions in 2020 in the order of magnitude of 40GtCO2/y and cumulative emissions around 2000GtCO2, this is valid for y=2%.

Temperature paths are rising at a constant rate of more or less 2% until 2070 for the RCP8.5% scenario. For other RCP scenario's 2.6, 3.4 and 6.0 the growth rate of temperature starts at 2% but approaches 1% in 2030 2040 and 2045 respectively. If there is no risk involved, our formula 3 only requires a mean growth rate of the SCC, which are shown in Table 3.

Concave increasing marginal damages

On very long time horizons, marginal damages do not increase at constant rate. At some point in the future, be it because fossil fuels are exhaused, temperatures will stabilize. Therefore we consider a trajectory of marginal damages converging over time towards a maximum. For the sake of brevity, from here on, we will use the shorter notation for the marginal damage per unit of CO2 $D_S = \zeta D_T$ and assume that there is no lag between emissions and marginal damages ($\xi = 0$).Assume marginal damages approach a steady state D_S^* at a constant rate x. $D_S = D_S^* - (D_S^* - D_S^0)\, exp(-xt)$.

$$SVO_{\tau_1,\tau_2} = \int_{\tau_1}^{\tau_2} e^{-rt-\phi(t-\tau_1)} \left(D_S^* - \left(D_S^* - D_S^0\right) e^{-xt}\right) dt \tag{23}$$

$$= e^{\phi\tau_1} \left[\left[\frac{D_S^* e^{-(\phi+r)t}}{\phi + r} \right]_{\tau_1}^{\tau_2} - \left[\frac{\left(D_S^* - D_S^0\right) e^{-(\phi+r+x)t}}{\phi + r + x} \right]_{\tau_1}^{\tau_2} \right] \tag{24}$$

$$= e^{-r\tau_1} \left\{ \left[\frac{D_S^*}{\phi + r} \left(e^{-(\phi+r)\nu} - 1\right) \right] - e^{-x\tau_1} \left[\frac{\left(D_S^* - D_S^0\right)}{\phi + r + x} \left(e^{-(\phi+r+x)\nu} - 1\right) \right] \right\} \tag{25}$$

The above path for marginal damages can be compatible with several cumulative emissions paths. For example, marginal damages can be proportional to production $D_S = -\gamma Y S$ and cumulative emissions follow the path $S_t = \frac{D_S^* exp(-gt) - \left(D_S^* - D_S^0\right) exp(-(x+g)t)}{\gamma Y_0}$. As a result, emissions in the long run are negative and decrease at rate g, to offset the effect of increasing production on marginal damages $E_t = \frac{-g D_S^* exp(-gt) + (x+g)\left(D_S^* - D_S^0\right) exp(-(x+g)t)}{\gamma Y_0}$. For a simpler case, we can assume that marginal damages are γS and that cumulative emissions follow the path $S_t = S^* - (S^* - S_0)\, exp(-xt)$. As a result, emissions are exponentially decreasing $E = E_0 e^{-xt}$ with initial condition $E_0 = x(S^* - S_0)$. This leads to the following formula for the social value of the offset

$$SVO_{\tau_1,\tau_2} = \gamma e^{-r\tau_1} \left\{ \left[\frac{S^*}{\phi + r} \left(e^{-(\phi+r)\nu} - 1\right) \right] - e^{-x\tau_1} \left[\frac{(S^* - S_0)}{\phi + r + x} \left(e^{-(\phi+r+x)\nu} - 1\right) \right] \right\}. \tag{26}$$

A linear emissions path and quadraticmarginal damages

Assume a linear decreasing emissions path $E_t = E_0 - xt$. This implies a quadratic cumulative emissions path $S_t = S_0 + E_0 t - \frac{x}{2} t^2$. Temperature peaks at time E_0/x, when emissions are zero. To make notation easier, we assume that marginal damages are γS. [2] As a result, marginal damages follow a quadratic time path $D_{S_t} = D_{S_0} + \gamma E_0 t - \frac{\gamma x}{2} t^2$. [3] .

The value of the project writes

$$SVO_{\tau_1,\tau_2} = \int_{\tau_1}^{\tau_2} e^{-rt-\phi(t-\tau_1)} \gamma \left(S_0 + E_0 t - \frac{x}{2} t^2\right) dt \tag{27}$$

Integrate by parts

[2] For damages proportional to production, marginal damages are $Y_0 e^{gt} \gamma S$ The solution is the same provided that γ is replace by γY_0 and r is replaced by $r - g$

[3] An extension to another damage function that would also lead to quadratic marginal damages is straightforward

$$SVO_{\tau_1,\tau_2} = e^{\phi\tau_1}\left[\left[\gamma\left(S_0 + E_0 t - \frac{x}{2}t^2\right)\frac{e^{-(\phi+r)t}}{\phi+r}\right]_{\tau_1}^{\tau_2} - \int_{\tau_1}^{\tau_2} e^{-(r+\phi)t}\gamma\left(E_0 - xt\right)dt\right] \quad (28)$$

Integrate by parts a second time

$$SVO_{\tau_1,\tau_2} = e^{\phi\tau_1}\gamma\left\{\left[\frac{e^{-(\phi+r)t}}{\phi+r}\left(\overbrace{S_0 + E_0 t - \frac{x}{2}t^2}^{S_t} - \frac{\overbrace{E_0 - xt}^{E_t}}{\phi+r} - \frac{x}{(\phi+r)^2}\right)\right]_{\tau_1}^{\tau_2}\right\} \quad (29)$$

The social cost of carbon (the above formula with for period $0, \infty$) is not really meaningful because emissions on a linear path become ever more negative (and warming becomes negative in the very long run). Therefore, we will now assume that when emissions reach zero at time $t^* = E_0/x$,they remain zero. As a result, temperature peaks at $S^* = S_0 + \frac{E_0^2}{2x}$ and is stable thereafter. This gives the following social cost of carbon (using Equation (29) between time zero and t^* and adding the present value cost of constant damages $\frac{e^{-rt^*}}{r}\gamma S^*$ thereafter)

$$SCC_0 = \gamma\frac{e^{-rt^*}}{r}\left(2S^* - \frac{x}{r^2}\right). \quad (30)$$

Substituting out γ allows to calculate the adjustment factor for impermanence and risk. In case the project stops before emissions are zero $\tau_2 \leq \frac{E_0}{x}$ this yields the following formula

$$SVO_{\tau_1,\tau_2} = SCC_0 e^{\phi\tau_1}\left[\frac{e^{-rt^*}}{r}\left(2S^* - \frac{x}{r^2}\right)\right]^{-1} * \quad (31)$$

$$\left[\frac{e^{-(\phi+r)t}}{\phi+r}\left(\overbrace{S_0 + E_0 t - \frac{x}{2}t^2}^{S_t} - \frac{\overbrace{E_0 - xt}^{E_t}}{\phi+r} - \frac{x}{(\phi+r)^2}\right)\right]_{\tau_1}^{-\tau_2} \quad (32)$$

S5. Extended matrix of correction factors

IPCC Scenario	Risk at start	Risk at end	SVO Correction factors (max.duration, v)				SCC ($\$/tCO_2$) Damages ($\gamma$)	
(Temp in 2100)	$\tilde{\varphi}$	$\phi+\varphi$	25	50	100	∞	γ=0.0077	γ=0.0025
RCP 2.6	1000(low risk)	0	24%	44%	70%	100%	109	35
(1.8°C)		0.25	23%	42%	63%	83%	109	35
		0.5	23%	40%	58%	71%	109	35
	0.5	0	23%	43%	69%	99%	109	35
		0.25	22%	40%	62%	82%	109	35
		0.5	21%	38%	56%	69%	109	35
	0.25(high risk)	0	21%	41%	67%	97%	109	35
		0.25	20%	39%	60%	80%	109	35
		0.5	20%	36%	54%	68%	109	35
RCP 3.4	1000	0	19%	37%	66%	100%	142	46
(2.6°)		0.25	19%	35%	59%	81%	142	46
		0.5	18%	33%	53%	68%	142	46
	0.5	0	18%	36%	65%	99%	142	46
		0.25	18%	34%	58%	80%	142	46
		0.5	17%	32%	52%	67%	142	46
	0.25	0	17%	35%	63%	97%	142	46
		0.25	16%	33%	56%	79%	142	46
		0.5	16%	31%	51%	66%	142	46
RCP 6.0	1000	0	17%	34%	64%	100%	161	52
(3.1°C)		0.25	17%	32%	57%	81%	161	52
		0.5	16%	31%	51%	67%	161	52
	0.5	0	16%	33%	63%	99%	161	52
		0.25	16%	31%	56%	80%	161	52
		0.5	15%	30%	50%	66%	161	52
	0.25	0	15%	32%	61%	98%	161	52
		0.25	14%	30%	55%	78%	161	52
		0.5	14%	28%	49%	65%	161	52

Table 4: Adjustment factors for non-permanence and risk. We assume a quadratic damages proportional to GDP $exp\left(-\frac{\gamma}{2}T^2\right)$ with damage parameters of Howard and Sterner (2017) (Column 8) as well as Nordhaus (2017) (Column 9). Temperature pathways evolve according to SSP1-RCP2.6; SSP4-RCP3.4; SSP4-RCP6.0 and an uncertain temperature path (Riahi et al. 2017, www.https://tntcat.iiasa.ac.at). Other parameters are $r = 3.2\%; \tau_1 = 3year; \zeta = 0.0006°C/GtCO_2; GDPgrowth = 2\%; T_0 = 1.2°C$. We use Equation (5) . For $\tilde{\varphi} = [0.5\ 0.25]$ the likelihood that the project is additional after 5 years is 92% and 71% respectively. For $\varphi + \phi = [0.0025\ 0.005]$ the likelihood that the project is additional after 50 years is 78% and 88% respectively. Under uncertainty, we assume a temperature path following one of the 3 RCP's with equal probability and a hazard rate with the same mean but increasing in temperature $\varphi_{uncertain} = \varphi_{certain}\left(0.5 + 0.5T/\bar{T}\right)$, where $\bar{T} = 2.01°C$,i.e. mean warming of the next 80 years in the 3 RCP's.

S6. The social value of an offset under multiple sources of risk

General formula

In this section we add risk from uncertain consumption and temperature in an expected utility framework. We calculate the expected utility of the project by multiplying future damages by future marginal utility in Equation (5) and discounting at the pure time preference rate. Diving this outcome by marginal utility today will result in the SVO expressed in monetary terms. Assuming a time separable utility function with constant elasticity of substitution $u = \frac{c^{1-\eta}}{1-\eta}$, a constant savings rate s ($c = (1-s)Y$), and initial time zero, the nominator in Equation (5) now becomes[4]

$$SVO^{utils}_{\tau_1,\tau_2} = \zeta\gamma \sum_{t=\tau_1}^{\tau_2} e^{-\delta(t+\xi)} E \left[\underbrace{\frac{c^{1-\eta}_{t+\xi}}{1-s}}_{Marg.\ Utility*Y} Q_t T_{t+\xi} \right] dt, \tag{33}$$

where Q_t is the stock of carbon. In case of failure or non-additionality, it is zero, unlike q_t in equation 5, which is defined as the carbon stored in the successful project.

Uncorrelated risks

Let's start by assuming that consumption c, the stock of carbon stored by the project q and temperature T are stochastic, but independent from each other. Equation (33) now becomes

$$SVO^{utils}_{\tau_1,\tau_2} = \frac{\zeta\gamma}{1-s} \sum_{t=\tau_1}^{\tau_2} e^{-\delta(t+\xi)} E\left[c^{1-\eta}_{t+\xi}\right] E\left[Q_t\right] E\left[T_{t+\xi}\right] dt, \tag{34}$$

Equation (34) shows that that there is no risk premium for temperature uncertainty. This follows from our assumption of a quadratic damage function, which results in a linear marginal damage. For convex marginal damages (power of total damages larger than 2), Jensen's inequality implies a positive risk premium increasing the SVO.

Similarly, there is no risk premium for the uncertainty regarding the stock of carbon in the project. In case the expected size of the stored stock is 1 and the hazard rate is ϕ is constant, we have $E\left[Q_t\right] = e^{-\phi t} q_t$ as in the main text.

[4]We assume a so-called 'open loop' optimization and abstract from Bayesian updating and policy learning over time, where optimal policy adapts to observed damages. Under Bayesian updating our expectations are conditional on the information set of the period before. See van den Bremer & van der Ploeg (2021) for thorough insights on uncertainty in a 'closed loop' optimization.

The effect of uncertainty on consumption depends on the choice of the inter-generational inequality aversion η. Some models (Golosov et al. 2014, Hambel, van der Ploeg 2021) use $\eta = 1$. In that case, consumption disappears from the Equation 34 and the social value of the offsetting project is independent of future consumption. Higher consumption decreases marginal utility and increases damages in a proportional way, exactly compensating each other. In the case of $\eta > 1$, the discounting effect dominates, $c^{1-\eta}$ is convex and Jensen's inequality implies that the expected value increases with uncertainty, increasing the value of the project. It can be shown that this boils down to a decrease of the risk-free discount rate (van den Bremer & van der Ploeg 2021).The opposite is true for $\eta < 1$, but in what follows we will assume that $\eta > 1$.

The risk adjustment will increase both the SVO and SCC. To see which effect dominates in the correction factor SVO/SCC, we combine Equation 1 and 2 and write the offset correction factor as

$$\frac{SVO_{0,\tau_2}}{SCC_0} = \frac{SVO_{0,\tau_2}}{SVO_{0,\tau_2} + e^{-r\tau_2} SCC_{\tau_2}}. \tag{35}$$

An adjustment of the discount rate has a larger effect on the SCC in the long run, i.e. a larger effect on the second term of the denominator $e^{-r\tau_2} SCC_{\tau_2}$ compared to the first term.Therefore, the correction factor decreases.

Correlated risks

What if temperature is correlated with consumption? Consumption and temperature can be positively correlated because larger production increases business-as-usual emissions, and leads to more emissions for a given effort of abatement. By contrast, a negative correlation is also possible. Good institutional design, political stability and international cooperation can both increase consumption and decrease emissions. Also, the damages from higher temperature will decrease consumption. Most studies find that correlation is small, but positive (Dietz, Gollier, Kessler, 2018).[5] When consumption and temperature are positively correlated and $\eta > 1$, $c^{1-\eta}$ and T will tend to be negatively correlated, decreasing the value of the project due to a negative covariance term. A positive climate beta boils down to a higher risk-adjusted discount rate, because the project has a procyclical return (Dietz, Gollier, Kessler, 2018, van den Bremer, van der Ploeg 2021). This will reduce both the SVO and SCC, but since an adjustment to the discount rate has a larger effect in the long run, it will increase the correction factor of the project, because the largest effect will be on the second term of the nominator in equation 35.

What if temperature and the quantity of carbon stored by the project are negatively corre-

[5]The elasticity of marginal damages with respect to consumption is known as the climate beta. If temperature is uncorrelated with temperature, our assumption of damages being proportional to consumption gives a climate beta of 1. Positive correlation between temperature and consumption will increase the climate beta beyond 1. Dietz, Gollier & Kessler (2018) find a climate beta of 1.06 for damages proportional to production and around 5% of production. They also assume that the expected marginal damages increase with the climate beta, such that the SCC increases with beta, whereas we focus on mean-preserving correlation in this section, such that the SCC decreases with beta.

Table 5: Overview of uncertainty effects. We assume a quadratic total damage function and $\eta > 1$. We consider mean-preserving spreads for an increase in uncertainty and

	Uncertain temperature* $\sigma_T > 0; \rho_{q,c} = \rho_{T,c} = 0$	Uncertain carbon stock $\sigma_q > 0; \rho_{q,c} = \rho_{q,T} = 0$	Uncertain consumption** $\sigma_c > 0; \rho_{c,T} = \rho_{c,q} = 0$	Consump
SVO	0	0	$\nearrow$	
SVO/SCC	0	0	$\searrow$	

*SVO increases and SVO/SCC decreases if total damage function is a power function with a power beyond 2.
** Effects are zero for $\eta = 1$ and reversed for $\eta < 1$

lated, for example because project failure rates are more likely under high temperatures? Both future temperatures and failure rates of projects may be driven by common factors such as government quality, the quality of property rights regime, wars, or high temperature may reduce the carbon storage through forest fires, droughts and floods. This would add a negative covariance term in equation 33 and reduce the expected value of the offset, because in the scenarios with highest marginal damages, the failure of the project is most likely. In Table 2 we produce the risk-adjusted SVO for this case. Since these failures only affect the SVO and not the SCC, the relative value of the project SVO/SCC will also decrease.

Private risk aversion vs socially optimal risk aversion

What if individual buyers apply a risk premium exceeding the social risk premium? Investors may fear reputational damage from failed projects or may price diversifiable risk. Diversifiable risk does not come with a social risk premium (only the mean success rate matters for the climate), but investors are unlikely to have a diversified portfolio of projects. As a result, individual buyers may have a higher risk-aversion compared to socially optimal risk-aversion and value a risky project below its expected social value in Equation (33). This higher risk aversion would be socially sub-optimal. Consider 2 projects with the same cost, but project A has a higher social risk-adjusted value (avoids more climate suffering in expectation) despite being more risky. It would be socially optimal to do project A, while the private market with an extra individual risk premium would finance project B.

Note also that individual risk-aversion is difficult to calculate because motivations for buying offsets are much more complex compared to standard financial assets. Motivations include altruism, green reputation, political reputation, strategic signals in international negotiations and ethical perceptions. These motivations will differ between buyers and are much harder to model for standard financial markets where agents are assumed to maximize a standard consumption-dependent utility function.

Conclusion

Table 5 gives an overview of our findings. Uncorrelated uncertainty regarding future temperature paths and the quantity of carbon stored by the project do not affect the SVO, using the expected future temperature and expected carbon storage will give the correct SVO. By contrast, uncorrelated uncertainty on future consumption increases the SVO. However, positive correlation between production and warming will decrease the SVO but increase the SVO/SCC ratio, while a positive correlation between temperature and the failure rate will shrink both the value of the project and the SVO/SCC correction factor. Finally, individual risk-aversion exceeding social risk-aversion leads to a hotter climate for a given offsetting budget and is welfare decreasing.

S7. Cost effectiveness framing

Climate change mitigation is frequently viewed in terms of cost-effectiveness. For instance, the carbon price in the UK reflects the marginal abatement cost of meeting a net zero target by 2050. Offsets can also be viewed as contributing to this target, with some caveats. Consider two approaches: 1) a project absorbing a tonne permanently; 2) a temporary project combined with a permanent project which starts immediately after the temporary projects ends, each absorbing a tonne of carbon. These approaches are equally effective in reducing emissions in the long-run. This yields a decision rule that favours approach 2) with the temporary project if it costs less:

$$C^P_{\tau_1,\infty} \geq C_{\tau_1,\tau_2} + e^{-r(\tau_2-\tau_1)} C^P_{\tau_2,\infty} \tag{36}$$

where $C^P_{\tau_1,\infty}$ is the cost of a permanent project at time τ_1. Assuming that we know the rate at which the cost of permanent projects increases over time, x, we have the equivalent of Equation (3) in the cost-effectiveness context, and the decision rule becomes:

$$C_{\tau_1,\tau_2} \leq \left(1 - e^{(x-r)(\tau_2-\tau_1)}\right) C^P_{\tau_1,\infty} \tag{37}$$

On an optimal trajectory, the cost of a project equals the social value: $C^P_{\tau_1,\infty} = SCC_{\tau_1,\infty}$, making the right hand side of Equation (37) the same as Equation (3).

However, in a non-optimal world, this approach is problematic. If intertemporal prices are not optimal, projects are ranked on the basis of prices that do not reflect their social value, and the decision rule in Equation (37) will not maximise welfare over time.

To illustrate, consider a carbon price that follows a cost-effectiveness approach, i.e. it yields the lowest discounted cost to stay within a given temperature target. In this case the carbon price follows a Hotelling path, increasing at the rate of discount so that $x = r$. Cost-effectiveness, by its very nature, is indifferent to the timing of damages and this leads to a carbon price that starts too low today and ends up too high in the future compared to a welfare-maximising optimal reaching the same long term temperature, but takes into account both the timing of the costs and benefits of mitigation. With $x = r$, Equation (37) indicates that a temporary project should only be realized if the cost is zero or negative. This criterion reflects the intuition that in a cost-effectiveness framework any temporary project that stops before the temperature constraint is met makes no contribution to staying below that temperature. Yet, it is impossible to value the delay of damages with a model that is indifferent to the timing of damages. Indeed, the expression for SVO_{τ_1,τ_2}in Equation (3) shows that delaying emissions through offsetting will have a positive social value.

This incompatibility of a cost-based approach with welfare maximisation in the context of offsets has important implications for some conventional approaches to valuing offsets. For instance, the formula of Carbon Plan (https://carbonplan.org/research/permanence-calculator-explainer) emerges after applying iterative substitution to Equation (36), and allows a comparison of the cost of a permanent project, $C_{\tau_1,\infty}$, with an infinite stream of temporary projects, C_{τ_s,τ_t}:

$$e^{-r\tau_1} C_{\tau_1,\infty} \geq e^{-r\tau_1} C_{\tau_1,\tau_2} + e^{-r\tau_2} C_{\tau_2,\tau_3} + e^{-r\tau_3} C_{\tau_3,\tau_4} + ... \tag{38}$$

The Carbon Plan formula assumes that all temporary projects have the same duration and the cost of a forestry project does not change through time. We obtain

$$C_{0,\tau_1} = \frac{C_{0,\infty}}{\sum_{i=0}^{\infty} e^{-r\tau_i}} \tag{39}$$

The previous discussion of cost-effectiveness explains why this formula is problematic. On a welfare maximizing path, the cheapest offsetting projects are realized first and as the SCC rises, more expensive projects are realized too. Therefore, a world were there are offsetting opportunities in the future at the same cost as today is a world where cost prices are not intertemporally optimized. This intertemporal inefficiency will lead to non-welfare-maximizing decision rules. Concretely, the hypothesis of cheap future offsetting opportunity is too optimistic, leads to the adjustment factor being too high, and offsets being overvalued.